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SYSTEM AND METHOD SUPPORTING TYPE CHECKING OF OPTIONS

RELATED APPLICATION(S)

This application is a Continuation-in-Part application of U.S. Application No. 09/672,848 filed September 28, 2000 which claims priority to U.S. Provisional Application No. 60/162,825 filed November 1, 1999, the entire teachings of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

In typical data processing systems, a compiler reads source code and creates the object code which is ultimately processed. Typically, the compiler creates a data structure which will support property values which are defined later in the source code or during run time. In an object oriented system, the compiler may create a class and a mechanism for creating instances of that class with defined fields of preallocated memory space into which the values are stored.

An alternative data structure which has, for example, been supported in the [incr Tk] language allows values to be stored in strings or arrays as options associated with an instance object. Using that data structure, memory space is only used for those properties which are given values since the space for those values is not preallocated. Rather, the space is only allocated when a value is optionally added to a list of values associated with the instance object.

SUMMARY OF THE INVENTION

In a data processing system, a class supports an option data structure having, in instances of the class, references to option values without preallocation of memory space for the full option values. The option data structure includes a type description of 5 the option value. During compilation, the type description in the option data structure is used to process an operation. For example, the declared type of a value to be set may be checked against that in the option data structure when the compiler processes a set operation. Also, the legality of an operation to be performed on a value obtained in a get operation may be checked based on the type description.

10 The option data structure may comprise a linked list of option items having option values. A nonlocal option value may apply to other objects in a nonlocal option hierarchy such as a graphical hierarchy.

15 The option data structure may additionally identify change handler code that is executed when an option value changes. Change handler code for one option may be defined in different classes within a class inheritance hierarchy, and change handler code from each class is executed when the option value changes.

20 A change handler may be identified by an option binding which may be located by first searching a mapping data structure for a previously computed mapping to the option binding. If no mapping was previously computed, the mapping to the option binding is computed and stored in the mapping data structure.

The option data structure may include a default value. In a get operation to an instance of the class, if an option value which applies to the instance has been set, the set option value may be obtained. If no value which applies has been set, the default value for the class is obtained.

25 Different classes may support option data structures of different forms. During compilation, an option operation, such as a get, set or is set? operation on an option value, is encoded as a method call to an object without regard to the form of the option data structure supported by the class. The ultimate form of the data structure is dependent on the called object.

The class supporting the option data structure may additionally include defined fields to support values in preallocated memory space.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

10 Figure 1 illustrates the use of an option list to define properties in accordance with the present invention.

Figures 2A illustrates an example class hierarchy with option binding lists to illustrate the present invention.

15 Figures 2B-2F illustrate an instance of a class type having different option item data structures.

Figures 3A and 3B present flowcharts of the procedure for finding a most specific option binding for an option item.

Figure 4 is a flowchart illustrating the process of getting a local option value.

20 Figure 5 is a flowchart illustrating the method of adding a local option value to an option list.

Figure 6 is a flowchart illustrating the method of running change handlers when a local option value is changed.

25 Figures 7A illustrates a hash table for rapidly identifying option bindings for options, and Figure 7B is a flowchart illustrating a process of using the hash table of Figure 7A.

Figure 8 illustrates a class hierarchy for graphical objects in a system embodying the invention.

Figure 9 illustrates an example class hierarchy with option binding lists for illustrating the use of nonlocal options in accordance with the present invention.

Figure 10 is a sample graphical hierarchy for illustrating principles of the invention.

5 Figure 11 is a flowchart illustrating the process of getting a nonlocal option value.

Figure 12 is a flowchart illustrating the process of determining whether a nonlocal option value has been set.

10 Figures 13A and 13B present a flowchart for the method of registering nonlocal options.

Figure 14 presents another graphical hierarchy for illustrating principles of the invention.

Figure 15 is a flowchart for the process of reregistering nonlocal options.

15 Figure 16 is a flowchart illustrating the process of adding a nonlocal option value to an option list.

Figure 17 is a flowchart for processing change handlers when a nonlocal option value is changed.

Figure 18 illustrates the use of a hash table for processing nonlocal options in packages.

20 Figure 19 illustrates relationships between objects in a graphical hierarchy that contains tables.

Figure 20 illustrates a typical personal computer in which the invention may be implemented.

Figure 21 illustrates details of the computer of Figure 20.

25 DETAILED DESCRIPTION OF THE INVENTION

A description of preferred embodiments of the invention follows.

The preferred embodiment of the invention is presented with respect to the Curl™ language developed by Curl Corporation of Cambridge, Massachusetts. The programming language is based upon a language developed at Massachusetts Institute of Technology and presented in "Curl: A Gentle Slope Language for the Web," 5 WorldWideWeb Journal, by M. Hostetter et al., Vol II. Issue 2, O'Reilly & Associates, Spring 1997.

Like many object-oriented languages (such as Java), the Curl language has the capability to define "classes" that have "fields." Within those fields, values of various properties of a class instance may be defined. For example, for a rectangle, parameters 10 of location, dimensions, color, font and so forth may be defined.

If a class C has a field x, and an instance c of the class C is created by an expression such as

let c:C = {C}

it is then possible to read the value of c's field x using the expression

15 c.x

and it is possible to set the value of c's field x using the statement

set c.x = new-value

Moreover, the compiler knows the type of the expression c.x based on the declared type of the field x. The compiler also can check that the new-value in

20 set c.x = new-value

is of a suitable type to be stored into the field x, and can issue an error message if this is not the case.

For each field that is defined for a class C, each instance of C will have some space set aside to store the value of that field.

5 Unlike other object-oriented languages, the Curl language has a mechanism known as "options" that works like fields but offers a different space/time tradeoff. An example is presented in Figure 1. Consider an instance 20 of a class which has several properties which must be defined for that instance. A field might be provided in the instance for each property and a value for that property provided in its associated field.

10 Where no value is provided, a default for the class would be used. However, where the use of defaults is the norm, providing a field for each property wastes memory space. In accordance with the present invention, fields may be provided for only those properties which are likely not to use the default. For example, values of property one and property 10 are included in fields of the instance 20. To allow for definition of other

15 properties, the embodiment of Figure 1 includes an options pointer to a linked list 22. Only those properties which do not have fields in the instance and which do not rely on the default value are included in that linked list. To determine a particular property (option) value, the system searches the linked list for the desired property, and if the property is not included in the list, relies on the default. The search of the linked list is

20 more time-consuming than directly accessing a value from a field, but there is a substantial savings in memory space where the number of properties which do not rely on the default value is small.

 In the example of Figure 1, any code which requires either property 1 or property 10 directly accesses the value 1 or value 10 from the associated field in the instance 20.

25 If, for example, property 8 is required, the system does not find that property in a field, and the system follows the option pointer to option item 24. The desired property 8 is compared against the key property 3 in option item 24 and when no match is found, the pointer to the next option item 26 is followed. Here the desired property matches the key of option item 26 and the value of property 8 stored in the option item is returned.

The system need not search further to the final option item 28. If property 7 were required, the system would search the option list, and not finding a match to any of the keys of the option items, would return the class default for property 7.

As will be seen, the same syntax is used to read or change values regardless of 5 whether the value is stored in the field or an option list. The compiler is able to respond appropriately in either case and provide the appropriate type checking.

There are two kinds of options: local and nonlocal. Local options are discussed immediately below. Nonlocal options provide a mechanism for propagating values from object to object and are discussed later.

10 Local Options

If a class C of the Curl language has a local option called y, the option's value can be accessed using the same expression syntax

c.y

that can be used for fields. The option's value can also be set using the same syntax that 15 works for fields:

set c.y = new-value

However, each option has a "default value" that is the initial value of that option when an instance of the class is created. If a class C has one or more options, then each instance of C contains an "option list" field that points to a (possibly empty) linked list 20 of "option items," each containing an "option key" and a value. If c is an instance of C and the expression

c.y

is evaluated, c's option list is searched to see whether it contains an option item whose option key corresponds to y. If so, the associated value is returned. If not, the default value of the option y is returned.

When the statement

5 set c.y = new-value

is executed, the result depends on whether c already has an option item corresponding to y. If so, the value in that option item can be replaced with new-value. (Alternatively, the existing option item can be discarded and a new option item created.) If there is not a previously existing option item corresponding to y, an option item corresponding to y 10 is created, new-value is put into it, and the option item is added to the option list of c.

The option mechanism also supports two other operations:

unset c.y

removes from c the option item, if any, that corresponds to y. This has the effect of restoring c.y to its default value.

15 {is-set? c.y}

returns true or false according to whether a binding for y currently exists on c's option list. This operation is needed in situations where it is necessary to distinguish the case where the option y has not been set (or has subsequently been unset) from the case where the option y has been set to a value that equals its default value.

The use of option lists makes it possible to define a very large set of possible options for a class without requiring the size of each instance of the class to be proportional to the number of possible options. The size of each instance is only proportional to the number of options that have been set on that instance.

5 Change Handlers

Every option declaration can define a "change handler," which is some code that is executed whenever the option's value changes. Thus, the most general way to declare a local option is as follows:

10 {local-option <name>:<type>=<default value>
 <change handler>}

The following is a concrete example:

15 {define-class Graphic {inherits OptionList}

 {local-option border-width:float=0.0
 {self.border-width-changed border-width}}

 ...}}

In this example, border-width is a local option of the class Graphic. The permissible values of this option are of type "float" and the default value is 0.0. Whenever there is a change (including a transition between set and unset) in the value of the border-width option for some instance g of Graphic, that instance's
20 border-width-changed method is invoked with the new border-width value as the argument.

If the change handler has been invoked because the option was unset, then the value supplied will be the option's default value. If the program needs to distinguish between the option's becoming unset and its becoming set to its default value, the change handler can use the is-set? operation to determine which is the case.

5 The change handler mechanism is integrated with class inheritance: if Rectangle is a subclass of Graphic, the definitions of both the Rectangle and Graphic classes can include option declarations for the same option, specifying different change handlers:

```

{define-class Graphic {inherits OptionList}

10      {local-option border-width:float=0.0
          {self.border-width-changed border-width} }

          ...}

{define-class Rectangle {inherits Graphic}

15      {local-option border-width:float
          {self.rectangle-border-processing border-width} }

          ...}

```

In this situation, if the border-width option of an instance of Rectangle is set, both change handlers will be invoked. This allows a subclass to extend the change handling that is performed by its base class. Note also that the default value need not be 20 repeated in the subclass's option declaration.

Implementation of Options

The Curl compiler processes the option declaration and therefore knows which option names are valid for any given class, and also knows the declared type for each such option name. Accordingly (and significantly), it can perform type checking on 5 uses of options in exactly the same way as it can type-check uses of fields. Assuming that the type check reveals no problems, the compiler generates code for each of the fundamental option constructs by translating them as follows:

	c.x	becomes	{c.get-option <x>}
	set c.x = 17	becomes	{c.add-option <x> 17}
10	unset c.x	becomes	{c.remove-option <x>}
	{is-set? c.x}	becomes	{c.option-set? <x>}

The notation <x> represents an "option binding" generated by the compiler that serves as a key for option storage and lookup. Each class that contains an option declaration for x has an associated option binding for x. When the compiler compiles a 15 reference such as c.x, where c is an instance of a class C, the compiler locates the most specific option binding for x that is in the class C or one of its superclasses. The lookup algorithm used for this process is exactly the same as is used when compiling references to fields. Thus, if C itself contains a declaration of the option x, the binding associated with that declaration is used. If not, then if C's base class D has such a declaration, D's 20 binding is used. If not, the algorithm proceeds in the same fashion until a declaration of x is located. The term "most specific option binding" is used for the result: this computation is said to return the most specific option binding of x in C.

In cases such as the Rectangle/Graphic example above, where declarations of the same option occur at multiple levels of the class hierarchy, the associated option 25 bindings are linked together. The option binding corresponding to Rectangle.border-width contains a "superclass binding pointer" that points to the option

binding corresponding to `Graphic.border-width`. Each option binding also contains a "base class binding pointer" that points directly to the end of the chain of superclass binding pointers, providing a quick way to reach the option binding corresponding to the given option name that lies closest to the root of the class hierarchy. This "base class" 5 option binding" has a special role in the option implementation. One aspect of this role is that the default value of the option is always stored in this binding. Other aspects are discussed later.

Each of the methods `get-option`, `add-option`, `remove-option`, and `option-set?` is a method of the abstract class `OptionCache`. All classes that contain option declarations 10 inherit, directly or indirectly, from `OptionCache`:

```
{define-class abstract public OptionCache
  {method public abstract {get-option key:OptionBinding}:any}
  {method public abstract {add-option key:OptionBinding, value:any}:void}
  {method public abstract {remove-option key:OptionBinding}:void}
15  {method public abstract {option-set? key:OptionBinding}:bool}
  }
```

The Curl language has a concrete class `OptionList` which is a subclass of `OptionCache` and which provides the linked list of option items described above:

```
{define-class public OptionList {inherits OptionCache}
20  field options:OptionItem
  Implementations of get-option, add-option, remove-option, and option-set?
  }
```

Thus, it is `OptionList` that actually contains the "options" field that points to the linked list of option items. The option key that is used in these option items is the base option

binding. OptionList includes the code required to get and change options in the option list.

Suppose we then define the following subclasses:

```

{define-class public A {inherits OptionList}
5   {local-option length:float=5.0
     {self.request-draw}
     }
     {local-option width:float=3.0
      {self.request-draw}
10  }
     Other code
  }

{define-class public B {inherits A}
  Code that does not involve the length or width options
15  }

{define-class public C {inherits B}
  {local-option length:float
   {self.tell-user length}
   }
20  Other code
}

```

When these definitions are compiled, the compiler generates an OptionBinding object corresponding to each local-option declaration in the program as illustrated at 30, 32 and 34 of Figure 2 A. Each OptionBinding object has fields including the following:

- name: the name of the option
- nonlocal?: true if the option is a nonlocal option
- type: the type of values to which the option can be set
- default-value: the default value of the option, or else null
- 5 has-change-handler?: true if the option declaration included a change handler
- change-handler: a procedure containing the code for the change handler, if one was specified
- superclass-option-binding: the OptionBinding, if any, corresponding to the closest declaration of this option in a superclass
- 10 base-option-binding: the OptionBinding that is reached by following the superclass-option-binding links repeatedly until the last OptionBinding in the chain is reached
- next: used to build a linked list of the OptionBindings that correspond to declarations in a particular class
- 15 The compiler also generates an object 36, 38, 40 to describe each class (e.g., A, B, and C); each of these objects points to a list of all the OptionBinding objects corresponding to option declarations appearing in the definition of that class.
- More specifically, class type object 36 for class A points to its base class OptionList. It also points to a linked list of its option bindings including bindings 30 and 32. Option binding 30 is for the property "length" and option binding 32 is for the property "width." The fields are filled in accordance with the class definitions presented above.
- 20 Class type B 38 references its base class A 36 from which it inherits, and also points to a linked list of option bindings. Those option bindings do not involve the length or width options and thus are not illustrated in this example.
- 25 Class type object C 40 inherits from and refers to its base class B and also points to an option binding linked list which includes an option binding for the property "length." In this case, superclass A has the only other declaration of length, so both the

superclass-option-binding and base-option-binding pointers point to option binding 30 of superclass A.

Figures 2B through 2E illustrate four possible instances of class C. In Figure 2B, the instance object points to the class type 40 for class C in Figure 2A. It may 5 include values in other fields. In this case, the option pointer is null so the default values are used for all properties not included in fields. In particular, the length and width values are both taken as the defaults of option bindings 30 and 32 of the base class A.

In the case of Figure 2C, the length option of this instance is explicitly set to 12 10 and the width option is set to 8. The instance still points to the class type object 40 and additionally has a pointer to an option list including option items 46 and 48. Within that linked list, option item 46 includes as its key a pointer to the base option binding 30 for class A, "length," and the option item 46 also includes a value of 12. The option item 48 includes as its key a pointer to the base option binding 32 of Figure 2A and a value 8.

15 If another option for the color blue were added, the linked list would be extended as illustrated in Figure 2D. The key for option item 50 would point to a base option binding for color, not previously described, as well as the value blue.

Finally, if the width option were unset, the option item 48 would be removed 20 from the linked list and the next pointer of option item 46 would be changed to point to option item 50 as illustrated in Figure 2E.

When an option item is added to an option list, the compiler must determine the base option binding to be inserted as the key in the option item. To that end, the compiler first looks to the class objects and their option binding lists to determine the most specific option binding. For example, if the instance is of Type C, the compiler 25 first looks to the option binding list of ClassType C object 40 for an option binding having an option name which matches that of the option item being created. For example, for a "length" option item such as OptionItem 46, option binding 34 is located. That option binding then provides the appropriate base option binding to be included as

the key in the option item. If a matching binding were not found in the option binding list of class C, the option binding list of the class ancestors of class C would be searched for the most specific option binding. In the case of the "width" option, for example, the compiler would next look to the option binding list of class B 38 and, finding no match,

5 would continue to the option binding list of class A 36. A match would be found at option binding 32, and since the base option binding field in that option binding points to option binding 32 itself, option binding 32 would be taken as both the most specific option binding and the base option binding and would be used as the key in the option item.

10 When the compiler compiles a reference to an option (e.g., x.length), it operates as in Figure 3A, using the subroutine get-option-binding of Figure 3B to find the most specific option binding b. At 31, c is defined as the class type object that represents x's type, n is the option name, such as length, for which the most specific option binding is being searched. At 31, the subroutine get-option-binding of Figure 3B is called. This is

15 a recursive routine which first searches through the option bindings list of the class c and then, if an option binding is not found, is called again to search base classes, that is, immediate parents of the class object. At 33, b is defined as the option bindings pointer of class c which points to the linked list of option bindings. For example, if the class type is object 40 of Figure 2A, the option binding pointer is a pointer to option binding

20 34. At 35, if there is an options binding list, b is not null and the name of the first option binding is compared to the name being searched at 37. If the names match, the most specific option binding has been located and is returned to 31 of Figure 3A. If the names do not match at 37, b is changed at 41 to the next pointer value of the option binding considered. Thus, the system loops through 35, 37 and 41 until a match is

25 found with the option name or the option binding list is completed.

Once the search of an option binding list is completed, the system defines the array bcs as an array of the base classes at 43. A base class is an immediate parent class. For example, class 38 is the base class of class 40. An index i is set to zero and a limit is set at the number of base classes in the array bcs. At 45, if it is determined that there

is a base class, the get-option-binding subroutine of Figure 3B is called for that base class. Thus, that parent option binding list is searched for a match with the option name. If there is no match, the system continues to that parent's base classes and so on. If no option binding is returned at 47, as determined at 49, the index *i* is incremented at 5 53 in order to call get-option-binding for another parent. Once all parents have been searched with no returned option binding, null is returned at 55 to 31. If the test at 49 shows that *bb* contains an option binding, then that option binding is returned to 31 at 51.

Once the get-option-binding routine is complete, either an option binding or null 10 has been returned at 57. If null is returned, a compilation error "Class member *n* not found" is returned. If an option binding was located, code for the requested option operation is emitted using the returned option binding as the most specific option binding.

When a program contains an operation to get a local option value (e.g., 15 *x.length*), the compiler translates that operation to a method call

{*x.get-option b*}

where *b* is the most specific OptionBinding for the length option for the ClassType object that represents the type of *x*. For example, in the case of an instance of class type C 40, *b* for the length option would be option binding 34. On the other hand, *b* for 20 the width option would be option binding 32 of ClassType A. The get-option-binding routine of Figure 3B would return the most specific option binding 32 for width by searching the class hierarchy.

The operation of the get-option method is illustrated in the flowchart of Figure 4. At 52, the variable *bb* is defined as the base-option-binding of *b*, and the variable *p* is 25 taken as the options pointer from the instance object (e.g., 42). If at 54, it is determined that the options pointer is null, the default value is returned from the base option binding at 56. In the example of Figure 2B, for example, the default value 5.0 is

returned from option binding 30. If the option pointer is not null, the pointer is used to access the first option item, and the key of that option item is compared to the base option binding at 58. If there is a match, such as at 46 in Figure 2C, the value of the option item 46 is returned at 60. If there is no match, the pointer p becomes the next 5 pointer of the option item at 62 and is checked for null at 54. The process proceeds until a value is returned.

Certain subclasses of OptionList use subclasses of OptionItem to represent the option items. This flexibility allows additional information to be attached to the option items for certain purposes. For example, Table class represents tables that have rows 10 and columns represented by the classes TableRow and TableColumn, each of which is a subclass of OptionList. The OptionItem subclass used by TableRow and TableColumn has an extra field for a sequence number that records the order in which options were set. Thus, when a given option is looked up by a table cell, its associated row and column are both queried for the presence of that option. If the option is set on both of 15 them, the conflict is resolved by returning the value associated with whichever option item was set more recently. Further information about this extension is presented below.

The separation between the abstract OptionCache class and the concrete OptionList class allows the Curl language to accommodate alternative representations 20 for the collection of currently set options. For example, OptionCache can have another subclass OptionHashTable that maintains a hash table of currently set options instead of storing the information as a linked list. Thus, classes that inherit from OptionHashTable instead of OptionList would rely on the hash table to define options. Since the compiler translates an option operation into a method call on an object, and it is the object which 25 defines the operations, the compiler need not specify a routine or be aware of the specific data structure used for a particular option.

For example, Figure 2F illustrates the case of an instance object 43 which points to a class type D. Class type D inherits from a class E which, in turn, inherits from OptionHashTable. The options pointer of instance 43 points to an Option Table 45,

rather than a linked list. Option Table 45 includes pointers to base option bindings of class E as keys and includes specific values for those keys. Only keys for which values have been set are included in the table.

Invoking Change Handlers

5 When an option item is created or modified, the associated change handlers need to run. First the most specific option binding is located by getting the option name out of the option key (base option binding) and then, using the routines of Figures 3A and B, finding the most specific option binding for that name in the class of the object whose option value has changed. This most specific option binding is the head of a
 10 chain of option bindings that can be traversed by following the superclass option binding pointers. Each of these option bindings has a field that may contain a pointer, supplied during compilation, to a change handler procedure. Each change handler found during this traversal is invoked.

15 Each change handler procedure is a procedure of two arguments. When invoking a change handler procedure, the first argument should be the object (instance) whose option changed, and the second argument should be the new value of that option for that object.

For example, when a program contains an operation to set a local option value (e.g., set x.length = v), the compiler translates that operation to a method call

20 {x.add-option b, v}

where b is the most specific OptionBinding for the length option for the ClassType object that represents the type of x. The operation of the add-option method is illustrated in the flowchart of Figure 5.

At 64, bb is defined as the base-option-binding of b, and a pointer index p is set
 25 equal to the options pointer of the instance object. If the pointer is null at 66, an option list is begun by adding an option item at 68, the option item having the base option

binding as a key and v as the value. Then, at 70, notification of the change is made as discussed below. If at 66, the pointer p is not null, it is used to access the first option item and the key of that option item is compared to the base option binding at 72. If there is a match, the value of that option item is changed to v at 74 and notification 5 through change handlers is made at 70. If at 72, the key does not match, the pointer index p takes on the value of the next pointer of the option item at 76 and the system returns to the null check at 66. The system continues to walk through the option list until the value is set in an appropriate option item or the next pointer is null and an option item is added with the value.

10 The subroutine {local-option-change-notify x, bb, v} runs the change handlers on the object x, for the option whose base option binding is bb, to notify the object's change handlers that the value of this option has become v. This subroutine operates as in Figure 6. At 78, c is the class type object that represents the type of the instance object. For example, for the instance object 42 of Figure 2C the class type object is 15 object 40 of Figure 2A. The subclass binding sb is determined as the most specific option binding 34 of class 40 having the same name as the base option binding 30 referenced in the changed option, item 46 in Figure 2C. One might expect that this binding sb would always equal the binding b referenced at 64 in Figure 5. However, this is not necessarily the case. The binding b will be the most specific option binding 20 for the class that is the declared type of the variable or expression x, but sb will be the most specific binding for the class that is the actual type of the value used for x. This latter class may be a subclass of the former class, and hence the most specific option bindings in the two cases may differ.

At 80, it is determined whether the subclass binding sb has a change handler. If 25 so, as in the case where sb is option binding 34, that change handler is called with the value v as the new option value at 82. Then, at 84, the superclass option binding of the subclass binding sb is followed. In the case of Figure 2A, the superclass option binding is the same as the base option binding, but in more complex cases, other intermediate classes may be referenced. If the option binding had no change handler at 80, the

system would in any case continue to follow a thread of superclass option bindings at 84. At 86, it is determined whether that new superclass option binding is null at 86, and if so, the routine is done at 88. If not, the change handler is checked at the next superclass option binding at 80 and the system continues.

5 Obtaining the most specific option binding is a potentially expensive operation, since it needs to be done at run time each time the value of an option changes. The straightforward implementation of this operation is a potentially expensive search of the data structures generated by the compiler when the classes in question were compiled, but there is a shortcut. A hash table, indexed by the option name and the class of the
10 object on which the option is being changed, can quickly yield the right option binding. When (as is currently the case in the Curl language) option declarations can occur only within class definitions, this strategy is safe because options on a class can only be set after instances of the class are created, which in turn can only happen after the class definition has finished being compiled. Once a class definition has been compiled, the
15 mapping between option names and their most specific option bindings for that class can never change, so there is no risk of the information in the hash table becoming invalid.

 A hash table to obtain most specific option bindings is illustrated in Figure 7A. Each entry in the hash table 90 includes a pointer to a class type object 92 and an option
20 name such as "length." It also includes a pointer to the most specific option binding for that option name of that class type 94. For example, if ClassType 92 in Figure 7A is the class type C 40 of Figure 2A, then OptionBinding 94 will be the option binding 34 of Figure 2A. To access an option binding through the hash table, a subroutine {get-option-binding-with-hash c, n} is presented in Figure 7B. At 96, the hash table is
25 checked for the (class type, option name) pair. If there is a match, the option binding found in the hash table is returned at 98. If there is no match, the hash table is updated by first running the get-option-binding routine of Figure 3B for that class and name. In that routine, the option bindings of the class and, if necessary, option bindings of its base classes, are searched for the required name. When the option binding is located,

the mapping to that option binding is stored in the hash table at 102 and returned at 104.

Alternative embodiments may allow options to be declared for a class after the class itself has already been defined and instances of the class have already been created. In that case, the declaration of a new option outside of a class definition will 5 need to invalidate the hash table so that it can be rebuilt from the new information in the class descriptors and option bindings. Since the declaration of new options is expected to be a very infrequent event compared to the setting of options and invocation of change handlers, the hash-table strategy will still provide a good performance improvement.

10 Nonlocal Options

Nonlocal options provide a mechanism by which the setting of an option value on one object can influence the value that is read using the same option name on another object. This sort of capability is useful, for example, in building hierarchies of graphical objects, where setting, say, the background color or font size on a table affects the 15 background color or font size of the objects within the table.

In the Curl language, this capability is currently used within graphic hierarchies, which are trees of graphical objects rooted (typically) by an object that represents a window visible on the screen. However, nonlocal options could be used in other situations not necessarily connected with graphics. Therefore, the nonlocal options 20 mechanism is formulated in terms of an "option hierarchy" that could be, but need not be, a graphic hierarchy. In the case of a graphic hierarchy, an object's option parent is generally the same as its graphical parent, and an object's option children are generally the same as its graphical children. However, there are cases in the Curl graphics system in which an object's option parent and graphical parent differ. Further, members of a 25 graphical (option) hierarchy are instances of classes which are members of a distinct class hierarchy. For example a text label may be a child of a VBox in a graphical hierarchy, and its type TextLabel may separately be a subclass of the Graphic class in a class hierarchy.

With nonlocal options, an option at one node of a graphical object propagates down through its children. When a change is made in the option at the root node, all of the descendants which make use of that option must be notified of the change and the change handlers for each of those descendants must be processed. With a get or is-set? 5 operation on local options, it is sufficient to check just the option list of the particular object of the method call, followed (in the case of a get operation) by use of the default value in the base option binding if the option is not within the option list; with nonlocal options, however, the option list of each ancestor in the graphical hierarchy must be checked for the option before the default value is returned. Similarly, with a change in 10 an option value, it is not sufficient that the change handler of the affected object and the like change handlers of that object's ancestors in the class hierarchy be processed. Rather, all associated change handlers must be processed throughout the class hierarchy of each affected descendant object in the graphical hierarchy.

An object in an option hierarchy can have one "option parent" and some number 15 (possibly zero) of "option children." If *b* is an object and *z* is declared as a nonlocal option, the evaluation of the expression

b.z

proceeds as follows. If there is an option item corresponding to *z* on *b*'s option list, the associated value is returned. If not, then if *b* has an option parent, the same operation is 20 repeated on *b*'s option parent and so on until either a value for *z* is found or an object with no option parent is reached. If no value is found anywhere along the chain, then the default value of the option is returned.

Similarly, when the operation

{is-set? *b.z*}

is performed on a nonlocal option z , the result is true if the option is set anywhere along the path of option parents starting with the object b .

Setting and unsetting of nonlocal options works in much the same way as with local options. In particular, when these operations are performed on an object, they

5 never affect the object's option parent or more distant option ancestors.

set $b.z = 17$

adds or updates an option item attached to b , and

unset $b.z$

removes the option item that is attached to b and corresponds to z ; if there is no such

10 option item, then the operation does nothing. A distinction from local options to be discussed below is that it is not sufficient that just the change handlers of class ancestors of the changed object be processed. Additionally change handlers of the object's graphical descendants and their class ancestors must also be processed.

A unique characteristic of nonlocal options is that it must be possible to set a

15 nonlocal option on any object d in an option hierarchy, even if the option is not explicitly declared in the class D of the object d or on any of D 's superclasses. This is required because, for example, in a graphic hierarchy one may want to set some option such as font-size on a container object that displays no text itself but which may have child objects that display text. To affect the appearance of all of these children with one

20 option assignment, the option must be set on the container.

This requirement is supported in the Curl language graphic hierarchies by establishing a common class `GraphicOptions` that is a subclass of `OptionList` and is a superclass of `Visual`, which is in turn a superclass of every graphical class. Ignoring other classes not relevant to this discussion, the resulting class hierarchy looks like

25 Figure 8.

If, say, the definition of the Rectangle class contains a declaration such as

```
{nonlocal-option background:any="white"}
```

an option binding for background will also be created in the class GraphicOptions, which means that the background option will be able to be set not just on a Rectangle

5 but also on a VBox, HBox, or any other Graphic.

Consider the following code whose compilation produces the data structure of Figure 9:

```
{define-class public GraphicOptions {inherits OptionList}
}
```

10 We can then define the following subclasses:

```
{define-class public Visual {inherits GraphicOptions}
{nonlocal-option font-size:float=10.0
}
```

Other code

15 }

```
{define-class public Graphic {inherits Visual}
Code that does not involve the font-size option
}
```

```
{define-class public TextLabel {inherits Graphic}
20 {nonlocal-option font-size:float
{self.request-layout}
}
```

```
Other code
}
```

The above definitions can be seen to compile directly to the class type object 110 from the GraphicOptions definition; to the class type object 112 having a "font-size" option binding 114 from the Visual definition; to the class type object 116 from the Graphic definition; and to the class type object 118 with "font-size" option binding 120 from the TextLabel definition. Further, when the nonlocal-option declarations are compiled, the compiler produces an Option binding for "font-size" 122 on the option-bindings list of GraphicOptions.

10 To avoid building knowledge of the GraphicOptions class into the compiler and restricting the options mechanism to the case of graphic hierarchies, the decision about where to create the base class option binding is implemented as follows. When a nonlocal option is declared for a class C, the compiler finds the superclass of C that is the closest to the root of the class hierarchy and contains concrete implementations of 15 get-option and the other methods that provide the interface to the options implementation (add-option, remove-option, and option-set?). In the above example, this superclass is OptionList. The base class option binding is then created at the immediate subclass of this class that is located along the path toward the class C. In the above example, then, the base class option binding is created in the GraphicOptions 20 class.

The provision of nonlocal options need not be coupled, as it is in the Curl language, with a strategy of storing option values in linked lists, even though the two approaches do complement each other well.

Figure 10 illustrates a set of instance objects in a graphical hierarchy. An 25 instance 130 of VBox has two TextLabel instances 132 and 134 as its graphical children. Each of the instances of TextLabel points to the class type for TextLabel 118 of Figure 9. Each refers to the instance 130 as its option-parent. Only TextLabel 134 has an OptionList pointing to the option item 135. Option item 135 has as its key a

pointer to the GraphicOptions. font-size option binding 122 of Figure 9. VBox also includes an OptionList which includes an option item 136 having as its key the option binding 122.

When a program contains an operation to get a nonlocal option value (e.g.,

5 x.font-size), the compiler translates that operation to a method call

{x.get-option b}

where b is the most specific OptionBinding for the font-size option for the ClassType object that represents the type of x. The operation of the get-option method when applied to a nonlocal option is illustrated in the flowchart of Figure 11.

10 At 138, bb is defined as the base option binding of b. To get the font size option of either text label 132 or text label 134 of Figure 10, that base option binding would be option binding 122 of Figure 9. At 140, the index p is defined as the options pointer of the instance under consideration.

Consider the TextLabel 134 where it is determined at 142 that the options
15 pointer is not null. Then, the pointer is followed to option item 135 where the key is compared to bb at 144. In this case, there is a match so the value 18.0 is returned from option item 135 at 146. If there had not been a match of the key, the linked list of option items would be followed by searching for a match of the key, changing the index key to the next value found in the option item. If no match were found in the option list,
20 p would be null at 142 for the last option item. Similarly, if the instance of interest were TextLabel 132, p would initially be null because the options entry of instance 132 is null. In either case, the option parent pointer would be followed at 150 to the parent instance, a distinction from local options where the default value would be immediately returned from the base option binding.

25 In the case of option item 132, the option parent pointer leads to the VBox instance 130. If at 152 it is determined that there is no parent instance, the default value of the base option binding is returned. In the above example, the value 10.0 would be

returned from option binding 122. However, if as in the example of instance 132 there is an option-parent, the index p becomes the option pointer of that parent and any linked list of that parent is followed in the loop of 142, 144, 148. In the example of Figure 10, the instance 130 points to option item 136 which, at 144, is noted to have a matching 5 key, so the value 24.0 is returned at 146.

When a program contains an operation to determine whether a nonlocal option value (e.g., x.font-size) is set, the compiler translates that operation to a method call

{x.option-set? b}

where b is the most specific OptionBinding for the font-size option for the ClassType 10 object that represents the type of x. The operation of the option-set? method when applied to a nonlocal option is illustrated in the flowchart of Figure 12.

The Figure 12 procedure is very similar to that of Figure 11 except that when a key is found to match the base option binding at 164, a true response is returned at 165, and once all linked lists of the instance and its parents have been searched to find no 15 match, a false is returned at 172. More specifically, at 158 bb is defined as the base option binding, and at 160 the index p is defined as the options pointer of the instance being reviewed. If that pointer is determined to not be null at 162, the key of the first option item is compared with the base option key at 164. The search of the option list continues through 166. Once the option list has been followed with no matches, the 20 option parent of the instance is determined at 168. If that option parent is not null at 170, the option list of the option parent is searched.

Propagation of Information in the Nonlocal Option Hierarchy

Change handlers can be specified for nonlocal options as well as for local options, but the logic for determining when to invoke a change handler for a nonlocal 25 option, and what arguments to supply to the change handler, is quite a bit more complicated than in the case of local options.

If a class such as Rectangle in the above example has a nonlocal option declaration such as

```
{nonlocal-option background:any="white"
{self.repaint-background background}}
```

- 5 then the repaint-background method of a Rectangle *r* will be invoked every time there is a change in the value of *r*.background. This means that the change handler needs to be invoked whenever the value of the background option is set at *r* or at any class ancestor of *r* whose background value is visible to *r* (i.e., is not shadowed by a value of the background option set at an intervening object). For efficiency, it is also desirable to
- 10 limit the propagation of option-change notifications to subtrees of the option hierarchy containing at least one object that has a change handler for the option in question.

These goals are satisfied by code in OptionList that can examine data structures produced by the compiler and can produce a list of nonlocal option names for which that object has change handlers. OptionList has a method register-options that can be

- 15 invoked to construct this list. Every object that can have option children must override this basic register-options method with additional code that asks the option children for their lists of registered options and merges all of this information into a list of options that is reported by its register-options method.

The operation of *x*.register-options when *x* has no option children proceeds via

- 20 Figures 13A and 13B. In Figure 13A the variable *c* is defined as the class type object that represents the type of *x*, e.g., the type of TextLabel 134 that has no children. An empty list *l* of option bindings is established and is to be filled through a recursive process in which the option bindings of each class ancestor of the object, such as TextLabel 134, are checked to determine whether they include nonlocal options of *c*
- 25 with change handlers. To perform that recursive search, a subroutine {register-class-options *c*,*l*} of Figure 13B is called. The completed list is a list of base option bindings for which this particular object, for example, TextLabel 134, is registering with the object OptionList for notification of any changes.

Figure 13B will be explained relative to the class definitions of Figure 9. At 202, the variable b is defined as the option bindings pointer of the TextLabel class type 118. At 204, b is determined to be not null since there is an option binding 120 on the class type 118. At 206, the option binding 120 is checked to determine whether it 5 includes a nonlocal option with a change handler. With both conditions true, the base option binding of option binding 120, i.e., option binding 122 is added to the list at 208 unless that option binding had already been presented in the list.

At 208, it is the base option binding of the option binding which is included in the list. The class GraphicOptions serves as a common class in which all graphical 10 objects can locate an option binding which can be recognized by every object in the graphical hierarchy. That is, the base option binding in GraphicOptions is a unique option binding to which all graphical objects refer when referring to an option such as the font size.

At 210, the system continues to follow the option binding list of class type 118 15 following the next pointers. Through this loop, each option binding of class type 118 which is nonlocal and has a change handler is added to the list. When that option binding list is complete, the system defines a set bcs which contains the base classes of class type 118, the immediate parents of class 118 from which the class directly inherits. The number of those class types is defined as the limit. In this case, class type 118 has 20 only one parent, class type Graphic 116, which is included in the set bcs. At 214, the limit is greater than zero so the limit has not been reached. Thus, at 216 the subroutine register-class-options is called for the specified parent. As a result, all of the parents of the parent 116 are ultimately processed recursively. Specifically, at 216 the option bindings of class type 116 are checked and through that pass of the subroutine register-class-options, all parents of class type 116 are similarly checked. Once all of the 25 ancestors of class type 116 have been checked through subroutine calls and all of the appropriate option bindings have been added to the list l, the index i is incremented at 218. In this case, there was only one parent to class type 118, so the limit is reached at 214 and the list is returned to OptionList at 220.

Once an instance object such as Rectangle 232 or TextLabel 234 in Figure 14 identifies an option for which it is registered to receive information, this option is included in the list of registered options in its parent VBox 230. That list of registered options is shown at 236. In the example of Figure 14, the Rectangle registers to be

5 notified about changes in the nonlocal option fill-color and the TextLabel registers to be notified about changes in the nonlocal option font-size. As a result, the registered-options field of the VBox points to a table of option names including both fill-color and font-size.

Some option parents in the Curl language follow this procedure to recompute

10 their registered option list each time they are asked for it. Other option parents save the registered option list when they compute it, and then just return the saved list of registered options if asked for it again. In either case, there is a need to notify option parents (and more distant ancestors) when a new object is added to the option hierarchy and has new option names to register. Thus, when an option parent p somewhere in the

15 hierarchy gains a new child c, it invokes the option-reregister-request method of its option parent q unless it can determine that the addition of c to the hierarchy does not change p's set of registered options. This invocation prompts q to recompute its own set of registered options and, if necessary, propagate the reregister request higher up in the option hierarchy. Similar processing could occur when removing an object from the

20 option hierarchy, to reduce its parent's set of registered options, but the Curl language does not implement a protocol for doing this.

Where an object such as VBox 230 of Figure 14 has a list of registered options, during the reregistration process it must not only register its own options but those of its children. This process is performed as illustrated in Figure 15. At 240, the register-class-options subroutine of Figure 13B is called for an object such as VBox 230, thus obtaining a list of nonlocal option bindings with change handlers for all class ancestors of VBox 230. A set of graphical children to the VBox 230 is defined as xc with a number of children nc. The set xc contains all immediate children but not the more remote descendants of the object. The index i is initially set at zero. In this example,

VBox 230 has two children 232 and 234 which are included in xc. At 242, the number of children nc is initially greater than zero, so at 244 the system initiates the register-options operation of Figures 13A and 13B for the first child rectangle 232. Recall that the process is a recursive process by which all nonlocal options having change handlers

5 are identified for the class Rectangle and all of the class ancestors of Rectangles. Recall also that, if the object xc[i] can itself have option children, then the definition of that object will override the register-options method shown in Figure 13A, adding processing to compute the options registered by the option children. The list of option bindings located in that operation are added to the list l. At 246, the index i is

10 incremented, and in the example of Figure 14, the system loops back at 242 to run the operation register-options for the TextLabel object 234.

Once the list l is complete, the list is used at 248 to complete the registered options list 236 for object 230. Further, the option-reregister-request is next applied to the graphical parent, in this case the graphical parent of VBox 230. Thus, the

15 reregistration process is required through the full ancestry of the graphical hierarchy, and at each object in that ancestry, all graphical children are caused to search their class hierarchies for nonlocal options having change handlers.

When a set or unset operation occurs on a nonlocal option z at an object a, the change handlers for z are invoked on a, just as though z were a local option. Then, each

20 option child c of a that has registered for option z is notified of the change. If the option z is also set at c, no action needs to occur at c because the value c.z shadows the value a.z. If the option z is not set at c, then c's change handlers for z (if any) are invoked and then the process is repeated for those option children of c that have registered for z.

When a program contains an operation to set a nonlocal option value (e.g., set

25 x.font-size = v), the compiler translates that operation to a method call

{x.add-option b, v}

where b is the most specific OptionBinding for the font-size option for the ClassType object that represents the type of x. The operation of the add-option method in this case is illustrated in the flowchart of Figure 16. By comparison of Figure 16 to Figure 5, it can be seen that the operation of setting a nonlocal option to an option list is

5 substantially the same as that of setting a local option. Specifically, from the definition of the base option binding and of the initial pointer to the option list at 252, the system searches the option list through the loop of 254, 256 and 258 to locate a matching key at 256. If that key is found, the value is changed at 260. If the key is not found, an option item is added to the list at 262. The difference in the two operations is that for nonlocal
10 options, the subroutine nonlocal-option-change-notify is called at 264.

The subroutine {nonlocal-option-change-notify x, bb, v} runs the change
handlers on the object x for the option whose base option binding is bb, to notify the
object's change handlers that the value of this option has become v. The change
handlers of x's option children and their descendants are also executed if appropriate.

15 This subroutine operates as in Figure 17. At 270, the local-option-change-notify routine
of Figure 6 is first called to process the change handlers of all of the superclasses of the
object x. In addition, it is determined from the register-options list of the object, such as
list 236 of object 230 in Figure 14, whether any children need to be notified of the
change in the option. At 272, it is determined whether the base option binding of
20 interest is present in the list l. If not, the process is done. If so, all graphical children of
the object are notified. At 274, all immediate option children of the object x, such as
object 230, are included in the set xc. The variable nc is set at the number of children,
and the index i is set at zero. At 276, nc is compared to i to determine whether there are
additional children to be notified. If so, at 278 it is determined whether the option
25 represented by bb is already set in the option list of the child. If so, no notification is
required and the index i is incremented at 280. If the option represented by bb is not
included in that child's list, the nonlocal-option-change-notify subroutine of Figure 17 is
called for that child. As a result, that child will notify its own change handlers and also

require that its children and their descendants notify their change handlers, if applicable.

Keyword Init Arguments

The Curl language allows both positional and keyword arguments to be supplied when an object is created. These arguments are supplied to the "init" (initialization) 5 method of the object's class. The Curl language also allows an init method to specify "..." in its formal parameter list, in which case the positional and keyword arguments that didn't match other formal parameters specified by the init method are packaged up into an array.

By convention, graphical objects in the Curl language interpret most keyword 10 arguments as specifications of options to set on the object, enabling the following sort of very compact initialization expression:

```
{VBox background="green", border-width=2pt, font-family="serif",
 15 {text bold?=true, Top Dog},
 {Rectangle width=2cm, height=1cm, fill-color="red"},
 {text Bottom of the Barrel}}
```

Thus, instead of requiring separate set statements for each option argument, the values of options such as "background" and "fill-color" can be set through the single initialization expression.

Among the mechanisms provided by OptionList (actually, by a superclass of 20 OptionList) is a method that can be used to scan for otherwise unmatched keyword arguments and apply them as option settings to the current object.

Packages and Sharing

The operating system process that executes Curl language computations is divided into a number of entities, referred to as CurlProcesses, that constitute the 25 different protection and storage management domains of the application. Thus, in a

Curl browser, each displayed page of content has its own CurlProcess, and system functions such as those that operate the "Back" and "Stop" buttons will operate within yet another CurlProcess. It is a goal of this architecture that packages of code can be loaded independently into the various CurlProcesses, so that certain classes would be

5 loaded in some CurlProcesses but not in others. For time and space efficiency, however, it is desirable that when the same package of the code is loaded into more than one CurlProcess, the executable code and immutable data structures associated with the package should be shared and not replicated.

This architecture creates some challenges for the options mechanism,

10 specifically the mechanism that creates OptionBindings for nonlocal options. If a package contains a class called Rectangle that declares a nonlocal option u, then according to the class hierarchy shown above, an option binding for u will be attached to the GraphicOptions class. However, the GraphicOptions class could be in a different package from Rectangle, and there could be some CurlProcesses in which both

15 GraphicOptions and Rectangle are defined, while in other CurlProcesses it might be the case that only GraphicOptions is defined. The option u should only be visible in those CurlProcesses where Rectangle is defined, but simple schemes for managing option bindings would attach the bindings directly to the shared data structures that represent the GraphicOptions class, causing the option u to become visible in all the

20 CurlProcesses.

To deal with this problem, the Curl language has a two-tier strategy for managing option bindings. Whenever an option binding attaches to a class that is defined in the same package that contains the option binding declaration, the binding is handled as described in the above presentation. If an option binding declared in a

25 package P needs to be attached to a class in a different package Q, however, Q's shared data structures are not modified. Instead, an entry including the option binding is made in a hash table that is private to the CurlProcess into which P is being loaded. Now, in order to determine whether a given class C has an option binding for an option z, a two-step lookup process is required. This process must check both the shared package

data structure and the CurlProcess-private hash table to see whether either of them contains the option binding of interest. Except for this difference, all of the implementation algorithms described above can be used unchanged.

In Figure 18, each package is represented by an object 290 of type Package, 5 which has a field "nonlocal-option-table" that points to a hash table 292. Hash table 292 maps ClassType objects to Option Binding objects representing nonlocal options that should be treated as though they were part of the chain of OptionBinding objects pointed to by the option-bindings field of the ClassType object.

The presence of packages changes the logic of "get-option-binding" (Figures 3A 10 and 3B) by adding more processing where Figure 3B returns null. When packages are present, the "Return null" step in that flowchart is replaced by a search of the data structures shown in Figure 18.

Table Row/Column Options

The option hierarchy model described above handles most of the requirements of 15 the Curl language's graphics system, but for tables a more sophisticated model is useful. In the case of tables, it is useful to be able to attach options to entire rows or columns, as well as to a table as a whole or just to an individual table element. The Curl language's package for displaying tables includes special extensions of the methods that do option lookup and option-change notification so as to implement this sort of "branching" in the 20 option hierarchy. Drawing the option parents above their children, the set of ancestors for an object in a table cell is illustrated in Figure 19.

The algorithm for looking up a nonlocal option's value at an object in the table is as follows:

1. If the option is set at that object, then return the corresponding value.

2. If the option is set at the cell then return the corresponding value. (The object that represents a table cell is defined so that its type is a subclass of `GraphicOptions`.)
3. If the option is set either at the row or at the column, but not at both, then return the corresponding value. (The objects that represent rows and columns are defined so that their types are subclasses of `GraphicOptions`.)
4. If the option is set at both the row and the column, find out which value was set more recently (using the subclassing technique discussed under "Implementation of Options"), and return that corresponding value.
- 10 5. If the option is set at neither the row nor the column, then continue searching for a value at the table or one of the table's option ancestors, in the usual fashion.

This scheme has the pleasant property that after executing the following code:

```

let t:Table = {Table}
set {t.get-column 2}.background = "green"
15      set {t.get-row 3}.background = "blue"

```

the background of the element at position (2,3) in the table will be blue (as will the background of all other elements in row 3), while the background of all the other elements in column 2 will be green. And if we invert the order of the assignments:

```

var t:Table = {Table}
20      set {t.get-row 3}.background = "blue"
set {t.get-column 2}.background = "green"

```

then the situation will be the same except that the element at (2,3) will now have a green background. This structure supports a simple semantic description in which, for example,

```
set {t.get-column 2}.background = "green"
```

5 can be interpreted as just meaning, "color all the cells in column 2 green" no matter what their color was before.

Implementation on a Computer System

Figure 20 shows an example of a computer system on which embodiments of the present invention may be implemented. As shown, Computer 1 includes a variety of 10 peripherals, among them being: i) a display screen 5 for displaying images/video or other information to a user, ii) a keyboard 6 for inputting text and user commands. Computer 1 may be a personal computer (PC), workstation, embedded system component, handheld computer, telecommunications device or any device containing a memory and processor.

15 Figure 21 shows the internal structure of Computer 1. As illustrated, Computer 1 includes mass storage 12, which comprises a computer-readable medium such as a computer hard disk and/or RAID ("redundant array of inexpensive disks"). Mass storage 12 is adapted to store applications 14, databases 15, and operating systems 16. In preferred embodiments of the invention, the operating system 16 is a windowing 20 operating system, such as RedHat® Linux or Microsoft® Windows98, although the invention may be used with other operating systems as well. Among the applications stored in memory 12 is a programming environment 17 and source files. Programming environment 17 compiles the source files written in a language that creates the output generated by embodiments of the present invention. In the preferred embodiment of the 25 invention, this language is the Curl™ language, developed by Curl Corporation of Cambridge, Massachusetts. The programming language is based upon a language

developed at Massachusetts Institute of Technology and presented in "Curl: A Gentle Slope Language for the Web," WorldWideWeb Journal, by M. Hostetter et al., Vol II. Issue 2, O'Reilly & Associates, Spring 1997.

Computer 1 also includes display interface 19, keyboard interface 21, computer bus 31, RAM 27, and processor 29. Processor 29 preferably comprises a Pentium II® (Intel Corporation, Santa Clara, CA) microprocessor or the like for executing applications, such those noted above, out of RAM 27. Such applications, including the programming environment and/or embodiments of the present invention 17, may be stored in memory 12 (as above). Processor 29 accesses applications (or other data) stored in memory 12 via bus 31.

Application execution and other tasks of Computer 1 may be initiated using keyboard 6 commands which are transmitted to processor 29 via keyboard interface 21. Output results from applications running on Computer 1 may be processed by display interface 19 and then displayed to a user on display 5. To this end, display interface 19 preferably comprises a display processor for forming images based on image data provided by processor 29 over computer bus 31, and for outputting those images to display 5.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.